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## From Discrete Dichotomies to Plural Paradoxes: Re-viewing Stratigraphical Time, Temporality and Change

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### **Abstract**

Stratigraphical time, temporality and change have frequently been studied and theorized through dichotomy, that is two opposed, “either/or” views. Linear versus cyclical and the principles of uniformitarianism versus catastrophism are classic examples. This paper aims to look beyond these simple tensions. It utilizes sequence stratigraphy as a lens to re-view established dichotomies and to explore the potential for a more paradoxical “both/and” interpretation. The main finding is that the two opposed linear versus cyclical views, can be reconceived as one synthesized sinusoidal view; other dichotomies are re-viewed which allow for spatiotemporal explanation and prediction.

### **Keywords**

Dichotomy — paradox — time — temporality — change — linear — cyclical — sinusoidal  
— uniformitarianism — catastrophism

## Introduction

### Father and son conversation

This dialogue took place in our tractor, as we topped the thistles and nettles in a horses' pasture. Four days prior, we had had our fifteen-year-old dog put down.

Son:        When you die, Mummy's going to be sad. And when Mummy dies, [my brother] and me will be sad. And when [my older brother] dies, I'm going to be sad. [pause] And on my own.

Dad:        Well you'll probably have your own family, with a wife and children and your own grandchildren.

Son:        Yes. [pause] And then it all starts again.

As my four-year-old son was beginning to explore in this pattern of family life, the linear and cyclical nature of time (objective time), temporality (the human perception of time, subjective time) and change (the change in the nature of some phenomenon through time), is an eternal duality. In *Time's Arrow*, *Time's Cycle*, Stephen Jay Gould (1987) set out to explore this timeless tension: on the one hand, linear time stretching out from the past into the future; on the other, cyclical time rotating in an infinite present that erases the past in its advance towards an imminent future. Gould is not alone. Many other scholars who have dared to grapple with the slippery concepts time, temporality, and change have done so through the dichotomy of linear versus cyclical (e.g., Adam 2004; Eliade 1949; Fraser 1975, 1987; Overton 1994; Rossi 1979).

Inspired by and in respectful contrast to these scholars, this paper has two aims: first, to re-view<sup>1</sup> this single dichotomy by suggesting that in fact the interlocking concepts of time, temporality, and change can be conceived as a series of discrete dichotomies; second, drawing upon contemporary scholarship in organizational sociology (paradox theory) and geology, (sequence stratigraphy)<sup>2</sup> to investigate the potential to re-appraise these discrete dichotomies as plural paradoxes.

This paper begins by introducing paradox theory, which differentiates dichotomy and paradox perspectives and polemicizes the benefits of the latter. It then describes a series of dichotomies of stratigraphical<sup>3</sup> time and change. The main body introduces sequence stratigraphy, a relatively recent theory that attempts to correlate strata based on time equivalent surfaces and sedimentary packages. The integrative potential of sequence stratigraphy, to re-appraise the unconnected dichotomies as a series of interconnected paradoxes, will then be discussed. The paper ends with conclusions about stratigraphical time and change.

## **1 Paradox theory**

Any scholar immersed in the details of an intricate problem will tell you that its richness cannot be abstracted as a dichotomy, a conflict between two opposing interpretations.

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<sup>1</sup> The word re-view, rather than review, is used as the phenomena of study (a series of –isms) are themselves views, perspectives, or stances. The paper is about reinterpreting a series of views; therefore re-view captures both the sense of “summarising past literature” and “relooking at previous perspectives.”

<sup>2</sup> This paper draws together literature on stratigraphy and management; a brief explanation may be required. The author studied geology as an undergraduate and carried out research in both palaeontology and sequence stratigraphy at Durham University, worked at the British Geological Survey and as a museum curator, and is a Chartered Geologist. After working up the career ladder, he did an MBA, discovered philosophy and social science, and is now completing a PhD in organizational strategy. This paper juxtaposes the early and late career of the author.

<sup>3</sup> Following Derek Ager’s *The Nature of the Stratigraphical Record* (1973), which had a profound impact on me during my first degree and is a major influence in this paper, the traditional English form “stratigraphical” (not the American English “stratigraphic”) has been adopted.

Yet, for reasons that I do not understand, the human mind loves to dichotomize. ...

(Gould 1987, 8)

Despite Gould's wise aphorism, he uses the dichotomy of *Time's Arrow*, *Time's Cycle* as a tool for his revolutionary and antithetical reinterpretation of Burnet, Hutton, and Lyell to clinical effect. But his argument against the "cardboard" straw men presented by Geikie's *Founders of Geology* (1905), hides a more subtle and synthetical view: not arrow or cycle, but arrow and cycle.

This transcendence resonates with a popular current vein of research in organization studies – paradox theory (Lewis 2000; Smith and Lewis 2011).

Conceptualizing paradox entails building constructs that accommodate contradictions.

Rather than polarize phenomena into either/or notions, researchers need to use both/and constructs for paradoxes, allowing for simultaneity and the study of interdependence. (Lewis 2000, 773)

This paper adopts Gould's term "dichotomy" for polarized phenomena with a mutually exclusive (either/or) relationship and Lewis's term paradox for interdependent phenomena with a mutually inclusive (and/or) relationship and is a response to Lewis's appeal that "researchers need to use both/and constructs" (*ibid.*). In particular, the aim is to re-examine the nature of stratigraphical change in order to explore whether traditional dichotomies can be re-interpreted as paradoxes. The next section introduces a number of traditional dichotomies and then, after introducing sequence stratigraphy, each dichotomy will be reviewed to explore the potential for a both/and paradox perspective.

## **2 Discrete Dichotomies**

This section outlines six dichotomies of time, temporality, and change. Each is considered to be discrete on the basis that "they are logically distinct. A coherent geological synthesis

could be constructed from any combination of these pairs of categories. Moreover, there would be no logical absurdity, or empirical improbability, in assigning different causes to different categories in this scheme” (Rudwick 1971, 212-3). In each case, its historical origins will be traced and any related contemporary debate will be explored.

## 2.1 Either Linearism or Cyclicalism

Linearism<sup>4</sup> occurs where the nature of change is viewed as a simple unidirectional process. In stratigraphy there are two great linearists. Nicolaus Steno (1669) developed the Law of Superposition, which can be summarized as follows: “In any continuum of strata, any stratum will be *younger* than the stratum on which it rests and *older* than the stratum that rests on it” (Kravitz, 2014, 692). Over a hundred years later, William Smith<sup>5</sup> developed the Principle of Faunal Succession (fig. 1), in which “each stratum contained organized fossils peculiar to itself, and might, in cases otherwise doubtful, be recognised and discriminated from others like it, but in a different part of the series, by examination of them” (William Smith, quoted in Phillips 1844, 15). Taken together, these linearists provide the foundation for stratigraphical change (Doyle and Bennett 1998; Rawson et al. 2002).

The opposing pole to linearism is cyclicalism, where the nature of change is viewed as a simple circular process. This is exemplified by James Hutton who developed “the most rigid and uncompromising version of time’s cycle ever developed by a geologist” (Gould, 1987, 79). Hutton had developed a theory of the earth and presented it to the Royal Society of Edinburgh in 1785 (published three years later), in which he postulated that the rock cycle was eternal:

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<sup>4</sup> Linearism, and its counterpart cyclicalism, are adopted from Haney (1969).

<sup>5</sup> A similar conclusion was drawn at a similar time by Cuvier and Brongniart in 1811 (Rudwick 1996; 1997, ch. 12).

We have now got to the end of our reasoning.... For having, in the natural history of this earth, seen a succession of worlds, we may from this conclude that there is a system in nature; in like manner as, from seeing revolutions of the planets, it is concluded, that there is a system by which they are intended to continue those revolutions. But if the succession of worlds is established in the system of nature, it is in vain to look for anything higher in the origin of the earth. The result, therefore, of this physical inquiry is, that we find no vestige of a beginning,--no prospect of an end. (Hutton 1788, 304)

Famously, Hutton is linked with two unconformities (fig. 1), one in the Scottish Borders at Jedburgh (found in 1787) and the other at Siccar Point on the coast near Eyemouth (found the year later), where he could see near vertical Silurian sediments overlain by near horizontal Devonian Old Red Sandstone (McIntyre and McKirdy 2012; Repcheck 2003). From this he deduced that the lower Silurian rocks had been laid down horizontally, compressed into folds, exposed above sea level and eroded flat, then covered by the later Devonian sediments, which neatly confirmed his earlier theory (Gould 1987).



Fig. 1. Hutton's unconformities: left – Jedburgh (Hutton 1795, plate 3); right – Siccar Point (Sutherland 2015).

Contemporary analogues to these foundational views can be found for both poles of this dichotomy. One branch of the emerging philosophy of geology literature draws upon the second law of thermodynamics to defend the unidirectional and irreversible nature of time (Kravitz 2013; 2014; in press). This is seen to be fundamental: “in geology, various physical laws are assumed and applied, but there is only one historical law that defines geology as a historical science”(Kravitz 2014, 27), which contains three time arrows:

the metaphysical time arrow, determining the order of events from past to future; the epistemic time arrow, according to which the past is closed...; and the causal time arrow, according to which every result in the present has causes rooted in the past. (Kravitz 2014, 20)

However there is also a current set of literature that holds to cyclicalism. These studies emphasize a wide range of cyclical patterns at different scales in the stratigraphical record, which range from lunar – tidal ~12.5 hours, spring-neap tide cycles ~15 days, lunar month ~29.5 days (e.g., Coughenour et al. 2009; Longhitano et al. 2012), through annual (e.g., Anderson & Dean 1988; Vaughan et al. 1989) and millennial scale (e.g., Bond et al. 1997; Tucker et al. 2009), to Milankovitch cycles – precession ~26,000 years, obliquity ~40,000, short eccentricity ~100,000 years, and long eccentricity ~400,000 years (e.g., Imbrie et al. 1992; Roe 2006), and up to multi-million year cycles (e.g., Melott, et al. 2012; Meyers & Peters 2011).

The contrast between a discussion about the second law of thermodynamics and cyclostratigraphy emphasise the essentially false nature of the dichotomy between linearism and cyclicalism in the stratigraphy, where linearism is about the nature of time and cyclicalism is about temporality (i.e., perceiving cyclical patterns may be a human tendency [Pollitt et al. 2014; Zeller 1964]) and/or change (real cyclical patterns in natural processes that leave real cyclical products in the geological record).



It may be that the dichotomy between linearism and cyclicalism is deep-rooted in many societies (e.g., Fraser 1975, 1987) and that it is a common way of exploring the nature of stratigraphical time, temporality and change (e.g., Gould 1987); however it is by no means the only frame of reference. The next three apparent dichotomies are all based on debates around uniformitarianism and catastrophism, each of which has been and continues to be a source of debate and contention.

## 2.2 Either Actualism or Possibilism

This is the first of three dichotomies,<sup>6</sup> the succeeding two being the subject of the next two sections, where the initial pole derives from Charles Lyell's *The Principles of Geology* (1830-33). The initial poles of each were collectively given the label "uniformitarianism," and opposite pole of each dichotomy was termed "catastrophism" (Whewell 1832).

Actualism (after Hooykaas 1963) is defined here as the view that products found in the geological record must be the result of processes that are actually observed at present (after Romano 2015): "the present is the key to the past" (Geikie 1905, 299, 403). Though originating from James Hutton, the "uniformity of process" (Rudwick 1972; Gould 1987) conforms to Lyell's subtitle: "An attempt to explain the former changes of the earth's surface by reference to causes now in operation" (Lyell, 1830).

In contrast, possibilism<sup>7</sup> is defined here as the view that products found in the geological record can be the result of processes that were different in kind and/or degree<sup>8</sup>

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<sup>6</sup> Rudwick (1972) and Gould (1987) discuss four distinct forms of uniformity; the foundational "uniformity of law" is taken as an *a priori* statement of the scientific method (e.g., Gould 1987; Kravitz 2014; Romano 2015) and has no opposing pole; therefore it is not discussed here.

<sup>7</sup> The antonym to "actualism" is often the negative "non-actualism" (e.g., Romano 2015). However, this term is not adopted as it could imply the pre-Lyell, religion-inspired supernatural causes (Sengör 2001) and *not actualism* would imply "the present is *not* the key to the past" which couldn't be further from the view of those Lyell opposed, for example Cuvier (Rudwick 2008, ch. 7). Therefore the term "possibilism," though not its meaning, is borrowed from philosophy (Menzel 2016).

<sup>8</sup> Degree here includes temporal duration, spatial extent, magnitude, and frequency.

from those at present. The necessary but not sufficient role of actualism is drawn out by George Cuvier:

Let us now examine what takes place on earth today ... since it has long been thought possible to explain earlier revolutions by these present causes... But we shall see that unhappily this is not so... The thread of operations is broken; nature has changed course, and none of the agents she employs today would have been sufficient to produce her former works. (Cuvier 1812, quoted in Rudwick 1997, 193)

Actualism and possibilism remain live topics. For example, actualism is supported by Donaldson et al. (2002) in their discussion of the Precambrian stratigraphical record and inferred ancient processes. By allowing for differences in degree between modern and ancient denudation and lithification, their understanding of actualism is so inclusive – for example including unique events – that the authors refute the utility of non-actualistic models. In contrast, it has been argued that possibilism is supported by a wide range of evidence, which indicate that processes were quite different during different periods of Earth's history (e.g., Baker, 2014; Gould 1987; Marriner et al. 2010; Romano 2015; Rudwick 1971, 1975). To illustrate this point, it has been argued that the complex feedback between life, atmosphere and Earth means that at different points in the past – for example before there was life on earth or before the Cambrian explosion – the processes acting would have been fundamentally different (Kirchner 2002; Kleidon 2010). So as Lyell and Cuvier were juxtaposed by Whewell in the early nineteenth century, actualists and possibilists continue to vie for supremacy over theories of temporal change.

### **2.3 Either Nonprogressionism or Directionalism**

Lyell's second form of uniformitarianism, the “uniformity of state” or nonprogression (Rudwick 1972; Gould 1987), was one pole of a historical dichotomy. As Lyell argued:

There can be no doubt, that periods of disturbance and repose have followed each other in succession in every region of the globe; but it may be equally true, that the energy of the subterranean movements has been always uniform as regards the *whole earth*. (Lyell, 1830, 53; italics in original).

Lyell went on to speculate “that the proportions of land and sea would have remained roughly constant throughout; and that the changes would not have been totally random, but arranged in the regular rhythm of what he called ‘the...geological cycle’” (Rudwick 2008, 307). Throughout geological time there was about the same amount of land, and as one landmass was eroded, another set of mountains was being built (Gould 1987).

Lyell’s nonprogressionist view seems particularly unempirical and dogmatic, as by the 1820s directionalism in both inorganic processes (cooling Earth) and organic processes (increasing diversity and complexity of life) was widely accepted (Rudwick 1971). However Charles Darwin’s *Origin of Species* (1859) marked the end of Lyell’s nonprogressionism (Bartholemew 1976; Rudwick 1998). It has been argued that Lyell had already reluctantly accepted directionalism during the 1850s (Gould 1987) and that he had even helped Darwin publish *Origin* (Hallam 1998), but by the 1860’s in a separate book *On the Geological Evidences of the Antiquity of Man* (written in 1863) and in his tenth edition of *Principles* (written in 1866-8), Lyell wrote in support of directionalism (Gould 1987; Hallam 1998; Rudwick 1998).

## **2.4 Either Gradualism or Saltationalism**

The “uniformity of rate” or gradualism, is a view that geological processes are slow, gradual and act over long periods of time (Gould 1987, Kravitz, 2013; Romano 2015; Rudwick 1974). In this third element of uniformitarianism, Lyell considered that stratigraphical change was the result of “the tranquil deposition of sedimentary matter” (Lyell 1854, 60).

Not that Lyell denied the impact of irregular events: “as we may predict the future occurrence of such catastrophes, we are authorized to regard them as part of the present order of Nature, and they may be introduced into geological speculations respecting the past, provided we do not imagine them to have been more frequent or general than we expect them to be in time to come” (Lyell, 1830, 89). Following Lyell, Charles Darwin was also a gradualist (Hallam 1998): “The old notion of all the inhabitants of the earth having been swept away by catastrophes at successive periods is very generally given up” (Darwin 1859, 317).

In contrast, saltationalism – proceeding by jumps or leaps – is a view that geological processes can be fast, abrupt and act over short periods of time with large impact (after Rudwick 1971). Again the archetypal protagonist, opposed by Lyell, is Cuvier, who argued that “several of the revolutions that have changed the state of the globe have been sudden” (Cuvier, 1804-5, quoted in Rudwick 1997, 85) and in relationship to the stratigraphical record, that “the changes ... have therefore not depended solely on gradual and general retreat of the waters, but on various successive advances [*irruptions*] and retreats... These repeated advances and retreats have not been slow at all, nor achieved by degrees: most of the catastrophes that led to them have been sudden” (Cuvier 1812, quoted in Rudwick 1997, 189-90).

Lyell and Darwin’s gradualism held sway for a century, until a change in zeitgeist marked by Kuhn’s *Scientific Revolutions* (1962), Eldredge and Gould’s *Punctuated Equilibria* (1972) and, of particular significance to this article, Ager’s *The Nature of the Stratigraphical Record* (1973) reignited interest in the debate between gradualism and saltationalism (Gould 1984; Marriner et al. 2010; Racki 2015). Though the balance has now tipped away from uniformitarianism, such that the preface to the third edition Ager was able to announce

that “catastrophism is back” (Ager 1993, xiii), interest in this dichotomy continues to be hotly debated (Miall 2015; Smith et al. 2015). The contemporary debate is not only between gradual and saltational change, but also the relative importance of sedimentary, volcanic, extra-terrestrial and, most recently, anthropogenic saltational impact (e.g., Baker 2014; Keller and Kerr 2014; Hallam and Wignall 1997; Knight and Harrison 2014; Smith et al. 2015).

At the start of this set of three dichotomies, the former in each pair were linked with Lyell’s uniformitarianism and the latter with Cuvier’s catastrophism. Yet the point has also been made, following Rudwick (1971), that each of these dichotomies is discrete and not interrelated to other elements. A brief explanation is therefore necessary. Whilst Lyell and Cuvier have acted as useful end members of a spectrum, intermediate views have been held. Charles Darwin is a case in point. He followed Lyell’s actualism and gradualism and famously wrote “I always feel as if my books came half out of Lyell’s brain” (Darwin 1844, quoted in Rhodes 1991, 196). However his long-term interest in the contemporary diversity of life, palaeontological evidence, and origin of species meant that, in contrast to Lyell, he was a progressionist from at least his late twenties (Rudwick 1982).

## **2.5 Either Continuism or Gapism**

This dichotomy is relatively recent. Though it relates to gradualism versus saltationalism, it emerged in the 1970s with Derek Ager’s apparently innocent, yet rhetorically hard-hitting question “What do we mean by ‘continuous sedimentation?’” (Ager 1973, 27). Over succeeding pages, Ager slowly attempts to deconstruct any vestiges of gradualistic naïveté

the reader may have, until one is left convinced of his chapter heading – there are “more gaps than record.”<sup>9</sup>

Gapism is the view that the geological record is dominated by gaps (fig. 2) and that these gaps are of interest in their own right: “it is the gaps in the record that provide much of its organizational structure, and hence its information content” (Smith et al. 2015, 2). In many respects it is a corollary of saltationalism, but it is distinct. The catastrophists of the early nineteenth century thought that in between brief, high impact saltational events there were longer periods of normal gradualism (Rudwick 1971). However contemporary gapists think that “for almost all of the time, almost everywhere, in almost every sedimentation system, nothing is happening. Deposition is not occurring; neither is erosion” (Tipper 2015, 105).

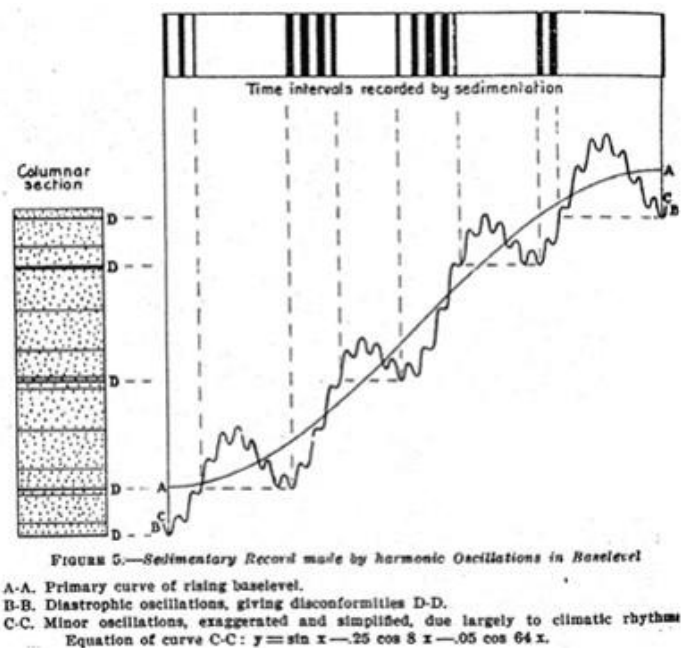


Fig. 2. An illustration from Barrell (1917, reproduced in Miall 2015) of how an apparently continuous stratigraphical record (left) can be made up of brief periods of preserved deposition (black bands at top) separated by significant gaps, which results from the

<sup>9</sup> As previously noted, Ager’s revolutionary *The Nature of the Stratigraphical Record* (1973) was published soon after Eldredge and Gould’s *Punctuated Equilibria* (1972) and Ager’s interest in gaps in the stratigraphical record is in consonance with the idea that “many breaks in the fossil record are real” (Eldredge & Gould 1972, 84).

interference between three phases of relative sea-level rise and fall: A – long term relative rise in sea-level; B – low frequency, high amplitude cycle; C – high frequency, low amplitude cycle.<sup>10</sup>

But this interest in gaps does not imply that an alternative does not exist. Continuumism is the view that the stratigraphical record is continuous between major hiatuses. Hilgen et al. (2015) present a major review that argues that “sedimentary successions can be continuous at Milankovitch time scales over millions of years” (ibid. 186). In short, this fifteen-author review presents varied sets of evidence from different sedimentary environments in different periods of geological time, where the stratigraphical record does not appear to contain any significant gaps. The debate between gapism and continuumism continues.

## **2.6 Either Decelerism or Accelerism**

This final pair of views is not an established dichotomy. However, after reading and reflecting on the nature of stratigraphical time, temporality and change, it seems that there is a sense in which slowing down and speeding up are significant. Decelerism is defined here as the view that temporality and/or change appears to be slowing down. This is most obviously demonstrated by the slowing down of the Earth’s rotation due to tidal friction (Varga et al. 1998; Varga 2006). Evidence that the length of day has increased through geological time comes from the microstructure of fossil growth bands in fossil corals, bivalves, and stromatolites (Johnson and Nudds 1975; Pannella, 1972; Scrutton 1978; Vanyo and Awramik 1985), as well as rhythmical tidal laminations in tidal sediments (Williams 2000). The oldest data from the base of the Proterozoic about 2.5 billion years ago suggests a length of day of 17-19 hours (Williams 2000, quoted in Varga et al. 2006),

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<sup>10</sup> Tucker et al. (2009) provide a real example: A – basin subsidence; B – short eccentricity Milankovitch rhythm (100-125ka); C – precession rhythm (~25ka). (In fact they go further in suggesting that there is a fourth, millennial-scale rhythm.)

whereas estimates for the length of day in the early Archean about 3.9 billion years ago, when life on Earth began, range from 15-17 hours (Varga et al. 2006) to 12-16 hours (Lathe 2006) and even as low as under 6 hours (Lathe 2004). In short, as the Earth's rotation slows down the days are really getting longer. On a finer scale, there are also parts of the stratigraphical column that record the shift from relatively expanded (i.e., a lot of sediment representing a short period of time) to relatively condensed (i.e., very little sediment representing a long duration), which documents a slowing rate of deposition.

In contrast to this, accelerism is a view that temporality and/or change appears to be speeding up. One form of accelerism is the parts of the stratigraphical column that record the shift from relatively condensed to relatively expanded deposition, which document an increasing rate of deposition. An example would be the sediments left by a river as it progrades forward into a lake or the sea: initially very fine clay would be deposited very slowly at a great distance from the river mouth, with a given period of time represented by a relatively thin layer of sediment; through time, ever more coarse sediment is deposited on top, with the same given period of time represented by ever thicker amounts of sediment. The second form of accelerism derives from our relative view of the stratigraphical record. From a geological perspective, the recent stratigraphical data is widely spread, rich in detail, easily observed, and equally easily interpreted; conversely there is less evidence of the very earliest stages of the Earth's formation, and what there is has been extremely altered and much more difficult to interpret – known as “the Pull of the Recent” (Jablonski et al. 2003). The psychological perspective also differs, from temporally proximal and relevant, to temporally distal and irrelevant (Wittmann 2016). Therefore we tend to place greater emphasis on the recent stratigraphical record and much less on the ancient past, as evidenced in the International Commission on Stratigraphy's illustration of chronostratigraphical time, which relatively expands the Cenozoic and contracts the





– have each been discussed separately at different times by different authors and can in principle be held in any combination to produce a coherent perspective. Yet taken together, they are a dissonant set of propositions, a cacophony of competing conceptions.

### **3 Sequence Stratigraphy**

Having introduced five typical dichotomies of time, temporality, and change, we can turn our attention to a theory that has emerged in the Earth sciences in recent decades – sequence stratigraphy. The overarching question, which I would like to reiterate here, is can we reconceptualize dichotomy as paradox? Sequence stratigraphy is introduced as a tool: not as a universal, law-like model for explaining and predicting any form of natural or social change, but as a metaphor that might act as a catalyst to initiate free-association about the poles of change.

#### **3.1 The Context of Other Stratigraphy**

Lithostratigraphy, based on the Law of Superposition developed by Steno (§2.1), describes rock units based on their rock type (e.g., Great Limestone Member or Millstone Grit Group) and tends to be the most micro-scale stratigraphical tool. The problem, in the context of this article, is that lithostratigraphical units bear little or no relationship to time. In brief, different rock types are formed in different environments that accumulate through time, but the boundaries between environments and rock units do not relate to time horizons (fig. 4).

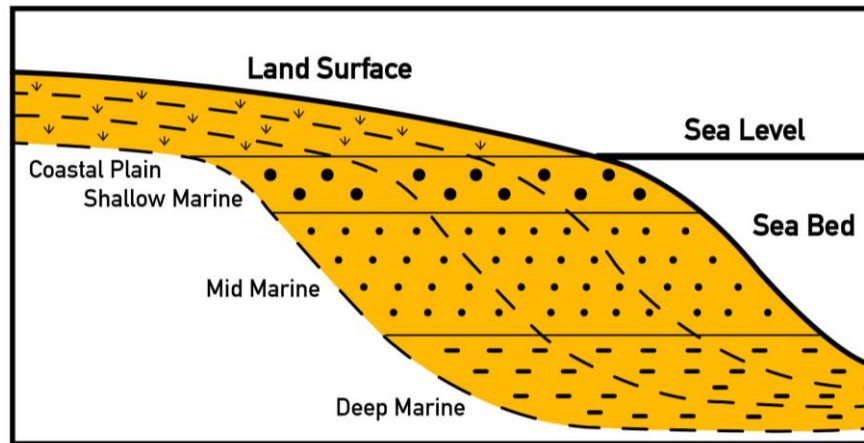


Fig. 4. Lithostratigraphy, showing four rock units being formed: coastal plain sediments containing vegetation, overlying coarse beach sand, overlying silty mid-slope sediments, and finally overlying deep marine muds. Crosscutting timelines are shown as dashed sigmoidal lines perpendicular to lithostratigraphical boundaries.

Biostratigraphy, based on the Principle of Faunal Success developed by Smith (§2.1), describes rock units based on a diagnostic fossil or assemblage of fossils (e.g., *Gnathodus bilineatus* Biozone) and tend to be a meso-scale tool. Whilst in good cases a fossil species – for example free-swimming, hard-shelled ammonites of the Jurassic – can be found in a variety of marine environments, many species are restricted to particular environments and therefore biostratigraphy suffers from similar constraints as lithostratigraphy.

In the context of this article, chronostratigraphy is the ultimate form of stratigraphy. It is the most macro-scale tool, whereby units are defined not on their constituents, but on their internationally correlated relative, and ideally absolute, age. So for example, at the Cretaceous-Tertiary boundary, it is now widely accepted that a meteorite<sup>11</sup> hit the Earth leaving a widely found layer enriched in iridium (Alvarez et al., 1980), which has chronostratigraphical significance – everywhere it is found, it represents the same moment

<sup>11</sup> Whether or not this was the sole, major, minor, or irrelevant factor in the demise the dinosaurs on land, the ammonites in the sea, and other groups, is more hotly debated (Keller and Kerr 2014; Sakamoto et al., in press).

in time. What is more, this horizon can be dated using radioisotopes to ~65.95 million years ago (Vandenbergh et al. 2012). So the ideal form of a chronostratigraphical boundary would be of global extent and marked in all depositional environments, normally in a period of continuous deposition, that is frequently and well exposed, contains abundant well-preserved fossils, and can be radiometrically dated (Rawson et al. 2002).

### **3.2 The Temporal Potential of Sequence Stratigraphy**

Sequence stratigraphy categorizes the rock record into packages of sediment bounded by time-significant surfaces, which are driven by variation in relative sea-level (Catuneanu et al. 2009). Regular rises and falls of relative sea-level leave predictable cycles of sedimentary packages – the set of packages left by one cycle of relative sea-level rise and fall (or fall then rise) is termed a sequence. Sequence stratigraphy originated in the late 1970s (Vail et al. 1977), though has its roots in the dawn of geology (Emery and Myers 1996). It was a tool developed in the oil industry to help explain repeated patterns of stratigraphical units seen in seismic surveys, though it has been expanded to include various scales and settings (Catuneanu et al. 2009; 2011).

Over the last four decades, sequence stratigraphy has been enthusiastically adopted by a wide range of geological sub-disciplines in industry and academia, leading to the development conflicting paradigms (Miall and Miall 2001). However, in recent years the leading theorists have come together to create a shared language and methodology (Catuneanu et al. 2009, 2010, 2011). One of the main contested aspects of the theory was the driving mechanism(s) (Miall and Miall 2001). One school advocated that global-eustatic sea-level change was the dominant driver, exemplified by cycles of glaciation and deglaciation (e.g., Vail et al. 1977). From this perspective, regular rises and falls of global sea-level produced regular packages of sediment bounded by temporal horizons with global

significance. The opposing school emerged as anomalies to the global-eustatic model increased and coalesced into a loose complexity school (Miall and Miall 2001). From this perspective, at least three mechanisms operated to form the regular packages of sediment: global-eustatic sea-level change (causing rise and fall of the sea-surface); local tectonics (causing rise and fall of the sea-bed); sediment supply – for example deposition of sand and mud by a river or delta – or the accumulation of carbonate material in a reef (causing the gap between sea-bed and sea-surface, termed “accommodation space,” to be infilled).

As this article addresses a non-specialist audience, for the sake of simplicity and clarity the following discussion will focus on a single variable – global-eustatic sea-level change. Essentially, if sea-level rises as it has done over the past 15,000 years due to melting polar icecaps, this results in shallow marine sediments being deposited over the top of what was previously coastal plain, and deep marine over shallow marine. It doesn't matter where on Earth (e.g., polar, mid-latitudes, or the tropics) or what type of environments prevailed (e.g., coral reef, beach, river mouth, stormy shallow sea, or calm deep sea), this deglaciation and global sea-level rise may leave a signature. Conversely, if the Earth's climate cools down, initiating a glacial period, then sea-level falls, causing shallow water sediments to be deposited over deeper water sediments and exposing the coastal plain and initiating incision by rivers. This is a signature that is potentially recognizable globally.

Each cycle of glaciation-deglaciation creates a regular set of four packages of sediments, which together make up a sequence (Catuneanu et al. 2009). To illustrate this essential detail of the sequence stratigraphy model, let us imagine an interglacial period like our own: there are small or no polar icecaps and sea-level is relatively high – a phase termed “highstand.” With constant deposition of sediment from rivers or deltas, relatively coarse sand-rich sediment is deposited inshore in shallow water and relatively fine silt and

mud-rich sediment is deposited offshore in deeper water. Through time, sediment builds up in successive dipping units and the shoreline migrates seaward (fig. 5a). Now let's assume that a new glaciation begins. As progressively more and more water is locked up in polar icecaps, sea-level slowly falls – a phase termed the “falling-stage.” During this period, successive layers of dipping sediment are deposited that step progressively downward into the basin. Also of significance, the area above sea-level is exposed with two results: first, there is a period of non-deposition across the newly formed coastal plain; second, river systems are rejuvenated, cutting deep incised valleys (fig. 5b). As the glaciation stabilizes, so does the sea level at a relatively low position – the so-called “lowstand.” Similar to the highstand, through time sedimentary deposition moves seaward in successive layers (fig. 5c). The fourth phase is caused by the melting of polar ice and relative sea-level rise – a phase termed “transgression.” During this period the shoreline moves landward for the only time. On what was exposed coastal plain, marine sediment is deposited (fig. 5d). The cycle begins to repeat when the deglaciation ends and sea-level stabilizes in a new highstand, related to a further phase of successive layers of sediment layering down into the basin, and the shoreline moving seaward (fig. 5e). These four phases can be represented on a sine curve, where the highstand is centred on the peaks, the falling stage is centred on the decreasing inflection point, the lowstand is centred on the troughs and the transgression on the rising inflection points (shown on the right of each part of figure 5).

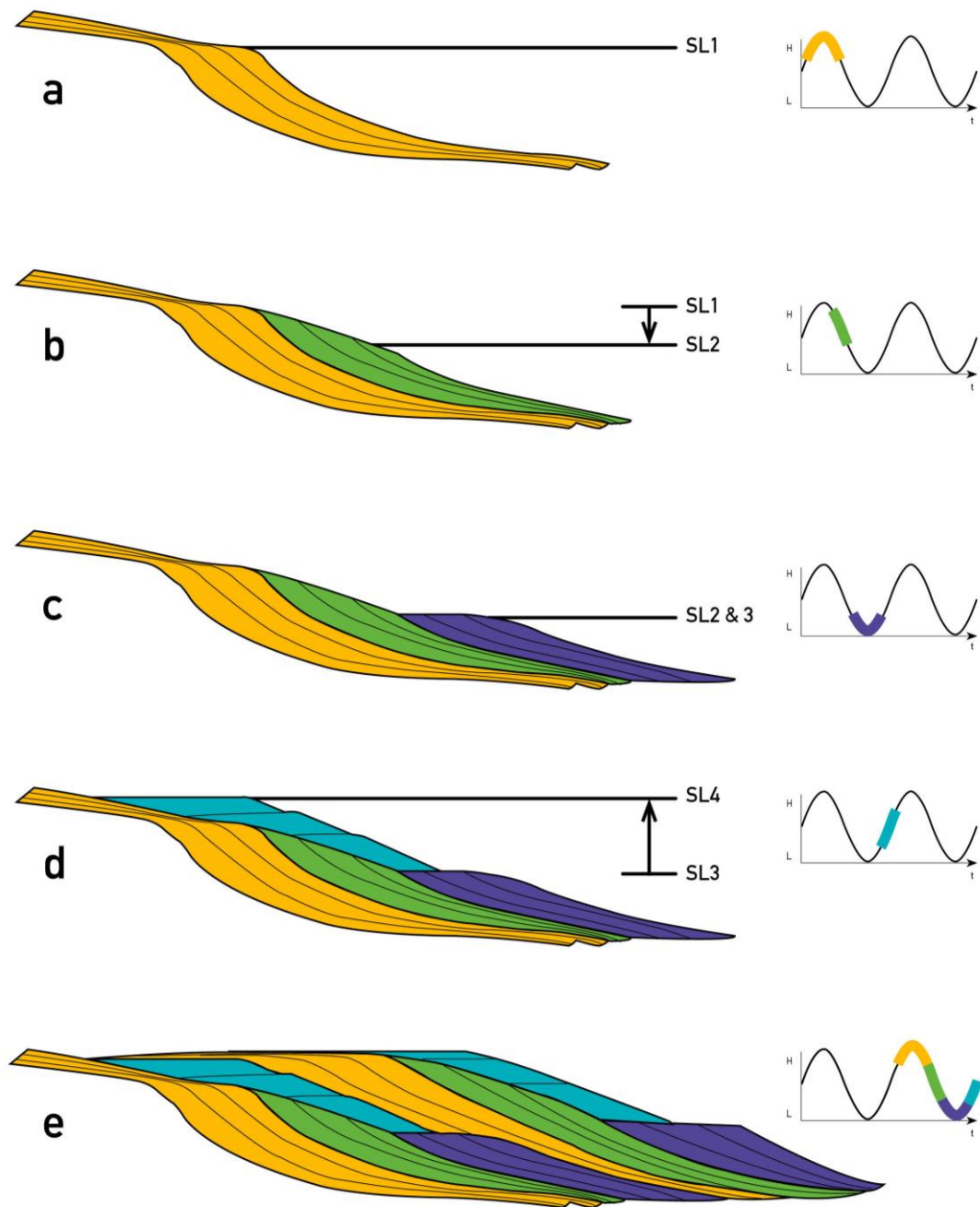


Fig. 5. Simplified illustration of the four repeating packages of sediment in a sequence stratigraphic cycle, where the vertical axis is depth/thickness, showing change in sea level (SL) and position on a sine curve of relative sea level (H=high, L=low, t=time): a. Highstand (yellow); b. Falling stage (green); c. Lowstand (purple); d. Transgression (sky blue); e. succeeding set of stages.

The potential power of sequence stratigraphy from a time perspective, is that it enables a set of strata to be analyzed for its temporal meaning. In short, a traditional lithostratigraphical or biostratigraphical interpretation where the vertical axis is thickness in meters can be re-presented with time as the vertical axis (fig. 6).

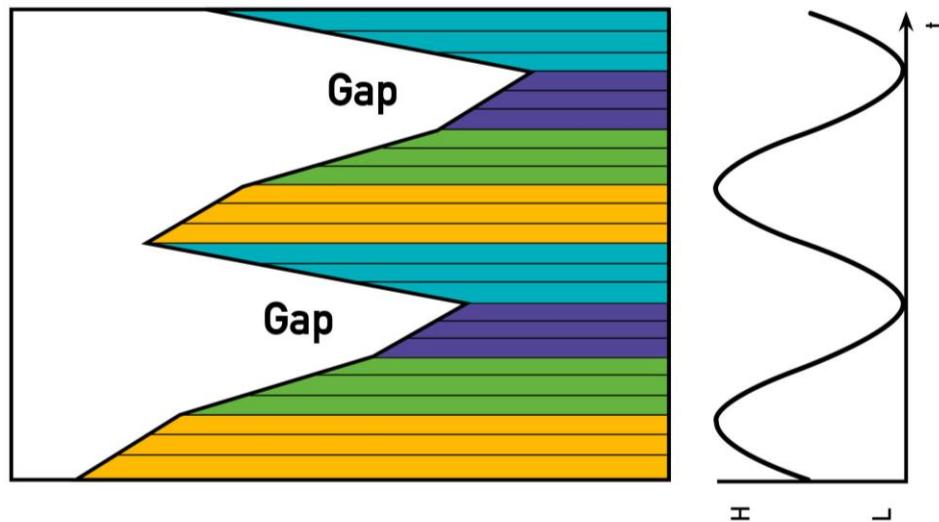


Fig. 6. Simplified illustration of two cycles of the four repeating packages in the sequence stratigraphy model (alternative representation of fig. 5e), where the vertical axis is time: Highstand (yellow); Falling stage (green); Lowstand (purple); Transgression (sky blue). The sine curve of relative sea level is shown on the right, with peaks linked to highstand and troughs linked to lowstand.

#### 4 Plural Paradoxes

This section tackles the central question of this article – Is there a way to synthesize the various perspectives on stratigraphical time, temporality, and change? The intention is to re-view the discrete dichotomies through the lens of sequence stratigraphy, looking specifically for a paradoxical “both/and” interpretation.



The first, and most significant, paradox to explore is “both linearism and cyclicalism.” Sequence stratigraphy encapsulates both poles of this traditional dichotomy in a paradoxical interpretation. In a normal stratigraphical sense, after Steno, sequence stratigraphy follows the principle of superposition with younger sediments overlying older sediments. In this sense, it concurs with the linearism view. However, the nature of the spatiotemporal relationships of the sediments are also driven by a cyclical change. Taken together, sequence stratigraphy offers a radical new view of the traditional linear versus cyclical tension where there is linear progression combined with rhythmical repetition. This goes beyond a simply paradoxical both linear and cyclical interpretation, to a novel, fully synthesized view of sinusoidal change.<sup>12</sup>

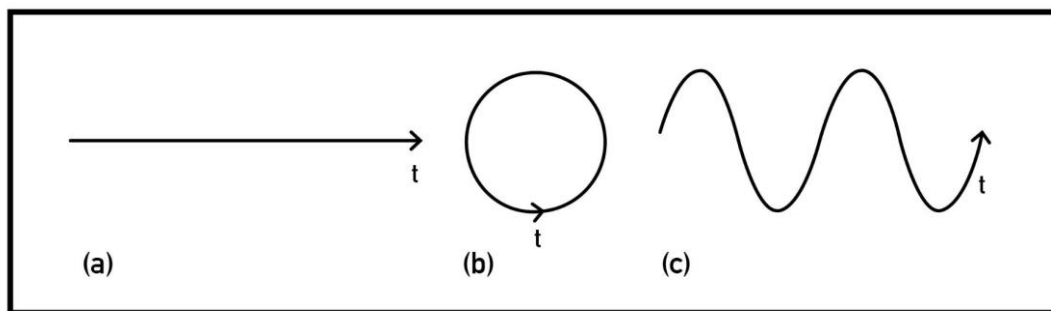


Fig. 7. Comparison between (a) linear, (b) cyclical, and (c) sinusoidal.

The second dichotomy to re-interpret as a possible paradox is “both actualism and possibilism.” Sequence stratigraphy helps us to understand when actualism may be sufficient and when it may be necessary but not sufficient. Whilst local tectonic and sediment supply conditions vary, globally we are currently in a relatively stable interglacial period (putting aside any influence of global warming); the current sequence stratigraphical setting is a highstand. Therefore, gathering empirical data on present sedimentary systems

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<sup>12</sup> A classic, smooth, repetitive wave form, which mathematically marries linear with cyclical.

will help geologists understand previous highstand periods. The present may also be a tolerable analogue for stable glacial periods represented by lowstand conditions. However, actualism cannot account for the geological record resulting from conditions during the falling stage and transgression. Therefore possibilism must be enacted to understand the global situation during such periods, though very carefully chosen locations exhibiting appropriate tectonic and/or sediment supply regimes may provide present analogues that can be extrapolated.

“Both nonprogressionism and directionalism,” the third paradoxical relationship to be explored, is aided by a sequence stratigraphical interpretation. Whilst nonprogressionism is a falsified steady-state view of stratigraphical change that even Lyell repudiated, it finds its best resonance during periods of highstand and lowstand. During these relatively stable periods of erosion, transportation, and deposition, the stratigraphical record documents steady progradation into deeper water. However during the falling stage and transgression, the sedimentary system is much more unstable and directional, with the stratigraphical record documenting rapid lateral shifts. Similarly the fourth pair of “both gradualism and saltationalism” show a link to different parts of the sequence stratigraphical cycle.

Highstand and lowstand may be linked to gradual change. This mimics the link of actualism and nonprogressionism and suggests a broadly uniformitarian link to the periods of highstand and lowstand. In contrast, the falling stage is more destructive, with erosion of the terrestrial realm and the dumping of a mass of sediment into deep water, which is overtly catastrophic in nature. Similarly transgression is catastrophic, as illustrated by the rise of sea level at the end of the last ice age (Lambeck and Chappell 2001), and would have flooded many rich coastal areas around the world, creating forced migration (Yanko-Hornbach et al. 2007; Turney & Brown 2007) and possibly linked to some of the varied origin myths around the world related to flooding (Dundes 1988).

The fifth dichotomy, re-viewed as the paradox “both continuism and gapism,” also finds synthesis in a sequence stratigraphical interpretation. Rather than perceive sedimentation as either continuous or full of gaps, sequence stratigraphy provides a way to theorize where we might expect to see gaps and where we might expect to see continuity in the stratigraphical record. Unlike the previous two paradoxes that found a form of temporal synthesis (vertically), continuism and gapism form a kind of synthesis spatially (horizontally). In relatively deep water we would expect to see relatively continuous sedimentation (fig. 6, right side), albeit that, when sea-level was at a maximum, the rate of deposition would be very slow indeed, creating a condensed section. Conversely, in the zone that alternates between terrestrial exposure and shallow marine deposition (fig. 6, left side), significant gaps will be left in the stratigraphical record.

The sixth and final paradoxical relationship is “both decelerism and accelerism.” In opposition to the traditional sense in which time is either slowing down or speeding up, sequence stratigraphy can be said to contain the effects of both. From the points of maximum and minimum sea-level, the rate of global sea-level change increases as sea-level falls or rises at an ever increasing rate respectively. From the points of inflection where these rates reach their greatest (half way down the sea-level fall or half way up the rise), the rates of change begin to slow down. So again there is a paradoxical relationship depending where in the stratigraphical record one looks.

In summary, sequence stratigraphy is a relatively new tool that offers a lens for re-viewing established dichotomies of stratigraphical time, temporality, and change. The most powerful synthesis is in reconceptualizing the either linear or cyclical dichotomy as a sinusoidal view of time, temporality, and change. However sequence stratigraphy also offers new ways to conceive of the other five dichotomies, such that they have a

paradoxical spatiotemporal relationship where both poles are present over the course of a sequence and the balance or dominance of each is explainable and predictable. To mirror the musical metaphor adopted previously, whereas a dichotomy perspective creates dissonance and cacophony, the paradox perspective enabled by the sequence stratigraphical lens creates melody and harmony.

## **5 Conclusions**

Stratigraphical time, temporality, and change have commonly been viewed in the past as a series of discrete dichotomies (e.g. ,Donaldson et al. 2002; Gould 1987; Kravitz 2013; 2014; Romano 2015; Rudwick 1971). It is argued that re-viewing the stratigraphical record through the prism of sequence stratigraphy offers two opportunities. First, it allows us to synthesize the either/or dichotomies into both/and paradoxes (Lewis 2000; Smith and Lewis 2010), which enables a more expansive and hopefully more accurate explanation of the stratigraphy. Most importantly, this also allows us to reconceive the principle dichotomy of either linearism or cyclicalism (Gould 1987) into a sinusoidal view of the stratigraphical change. Looking through the lens of sequence stratigraphy also allows us to reconsider the other five dichotomies, guiding when and where we might expect one or the other pole to be dominant or both to be in balance. Second, instead of our viewing each pole as discrete, a sequence stratigraphical lens encourages an interconnected perspective where all the elements of stratigraphical time, temporality and change are operating together, to a greater or lesser extent, through time.

The final conclusion is about the nature of the phenomena of study, distinctions that are often left undiscussed. Time, the objective time of the physical world (above the subatomic and quantum scale), is intensely and unavoidably linear (Kravitz 2013, 2014,

2016). Yet temporality, the human perception of time, is far more complex. This subjective time encapsulates both a linear (birth, maturity, death) and cyclical (one generation following another, imminence and eternal return, tides and seasons) (Adam, 2004; Eliade, 1949; Fraser, 1975, 1987; Rossi, 1979), but also biases towards perceiving recurring rhythms (Pollitt et al. 2014; Zeller 1964) and time speeding up (Wittmann 2016). But most pervasively, this article emphasizes the many ways that stratigraphical change has been perceived and its nature as a many faceted, interconnected phenomenon.

There are two directions for future research building on these conclusions. First, does this paradoxical view of stratigraphical time, temporality and change have implications for geologists or philosophers of Earth sciences? Second, does this analysis of stratigraphical time, temporality, and change, have wider utility beyond stratigraphy?

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